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A Review of Zinc-Oxide as Nano Materials and Devices

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Abstract— **This paper presents a review of zinc oxide (ZnO) as nano material and device. ZnO has gained substantial interest in the research area of wide band gap semiconductors due to its unique electrical, optical and structural properties. Recently, ZnO as nano material generates much interest among researchers and technologists and have been used in many devices such as UV photodetectors, light emitting diodes, solar cells and transistors. Moreover, a brief overview on ZnO recent advances on nanoparticles, nanowires and their applications as devices are discussed and reviewed.**

Index Terms— **ZnO, Nanomaterials, Nanodevices, Nanowires, Nanorods.**

I. Introduction

ZnO is a wide-band-gap semiconductor (3.3 eV) [1]. ZnO has a high exciton binding energy (~60 meV) compared with other semiconductors [1]. ZnO is optically transparent in the visible region and shows higher electrical conductivity with appropriate dopants. Due to these characteristics, ZnO is used as a transparent conductor. In the same way, ZnO is promising for use in light detecting devices that operate in the UV light wavelength of 375 nm. Recently, ZnO nanostructures have attracted a lot of research interests due to their unique structure, electrical, optical properties. ZnO, as a nano material, is becoming a very attractive for applications in electronics, photonics, acoustics, and sensing based devices [1]. ZnO also holds some potential in transparent thin film transistors (TFTs) owing to its high optical transitivity and high conductivity [1]. ZnO nanostructures devices utilizing nanowires and nanorods such as biosensors and gas sensors and solar cells, are relatively easy to produce. The structural properties of the ZnO also plays an important role. ZnO has a wurtzite structure as illustrated in Figure 1. It comprises hexagonal closed packed oxygen ions with half the tetrahedral interstices contain Zn^{2+} ions. Layers occupied by zinc atoms alternate with layers occupied by oxygen atoms. This structural property of ZnO makes it candidate for several nano based applications [1].

II. ZnO Nanostructures Material

ZnO nanostructures material exhibits many advantages for nano devices because of its higher surface-to-volume ratio as compared to thin films. ZnO nanostructures material has the ability to absorb ultra violet (UV) radiation and immense in many optical applications. ZnO has various nanostructures shapes including nanowires, nanoparticles, nanobelts, nanorings, nanotubes, nanodonuts,

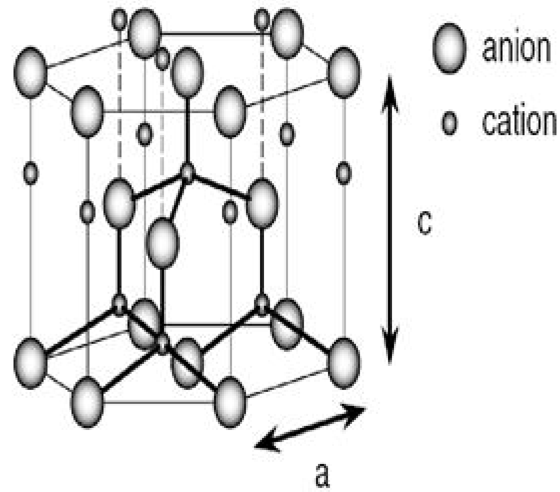
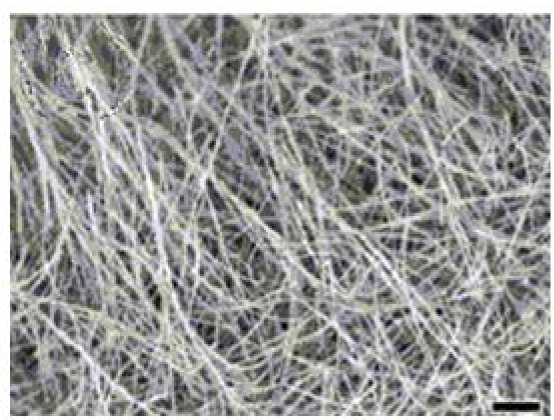


Figure 1. ZnO Wurtzite Structure

nanopropellers [2]. ZnO nanoparticles generated lot of interest among scientists as well as technologists during past few years. Particularly, the electronic properties of quantum confinement of electrons of nanoparticles make them very useful in electronic industry including many ZnO applications. Figure 2 shows a SEM of the ZnO nanostructures material nanowires and nanoparticles. Moreover, ZnO based nanoparticles has a wide range application such gas sensors, catalyst, pigments, optical materials, UV absorbers and additives in many industrial fields



a. ZnO nanowires

ZnO based nanoparticles can be fabricated using several methods. However, the productions of ZnO nanoparticles have many issues such as agglomeration and high production cost. Agglomeration free of ZnO nanoparticles can be successfully overcome by using mechanochemical processing technique and also it is found one of the most economical

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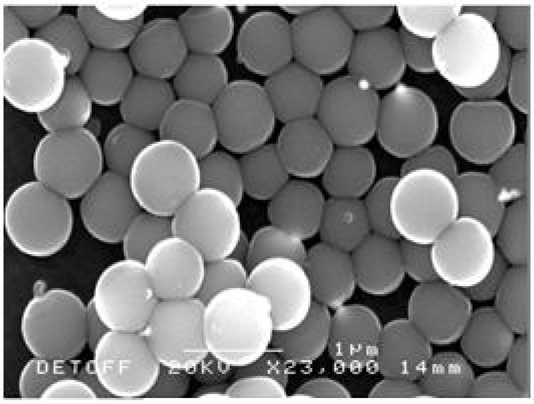

b. ZnO nanoparticles

Figure 2. ZnO nanowires and nanoparticles (Reference [11]).

methods [3] for their lower power consumption and photonics applications.

III. Doping of ZnO Nanostructured Materials

Controlled and appropriate doping of semiconductor nanostructures plays a vital role to develop novel materials and functional devices. The devices integration with high density and complimentary functionalities, developing appropriately doped semiconductor nanostructures is of fundamental significance and promising to exhibit better performance. However, doping nanostructures presents a challenging task due to the size effect and their tendency of self-purification. Doping of ZnO as a nanomaterial is considered one of the obstacles for many researchers due to the difficulty to performing this process. More ever, Doping high-quality *n*- and *p*-type of ZnO is also considered one of the major obstacles in many nanostructured device applications. Achieving the p-type doping of ZnO is one of the main limitations of producing efficient electronic and optical devices [4].

However, recent results show the p-type of ZnO can be obtained with the use of ZnMgO, Mn, Mg, and Cu dopants [5]. Recently, Magnesium (Mg) doped ZnO nanostructures were reported by Nursyahadah et al. [2]. It was found that Mg doped ZnO nanostructures by flame spray synthesis modifies the optical properties of the doped ZnO nanoparticles [6].

On the other hand, ZnO doped with Manganese (Mn) was reported by Sabri et al. [7]. ZnO, when doped with Mn, can form stable phase with hexagonal crystal structure over a wide range of composition [7] and has moderate solid solubility without phase segregation as the ionic radius of Mn (0.66Å) is closely to ionic radius of Zn (0.60Å) [8]. The Mn-doped ZnO nanoparticles results in Mn substitution into the nanoparticles. This is due to the increasing of the lattice parameter and unit cell volume with increasing Mn content. Figure 3 shows a Mn doped ZnO nanostructures.

On the other hand, cupper (Cu) doping of ZnO nanostructures was reported by reference Xing et al. [9]. Three different syntheses for Cu doped ZnO nanostructures were reported. Controlled doping appropriate elements into semi

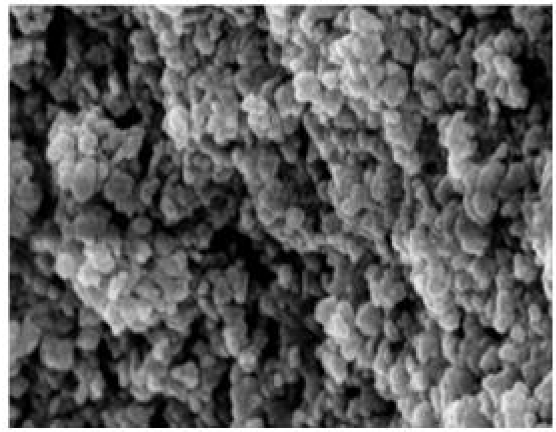

Figure 3. Mn doped ZnO nanostructures (From Reference [7])

conductor nanostructures are of vital importance to develop novel materials and functional devices. This is due to the size effect and their tendency of self-purification [10]. Cu is an especially interesting dopant because those Cu related compounds are not strongly ferromagnetic. Recently, a few research groups have synthesized and studied the physical properties of ZnO thin films [11]. However, there are only few reports on Cu doped ZnO nanostructures [12]. Figure 4 shows Cu doped ZnO nanostructures.

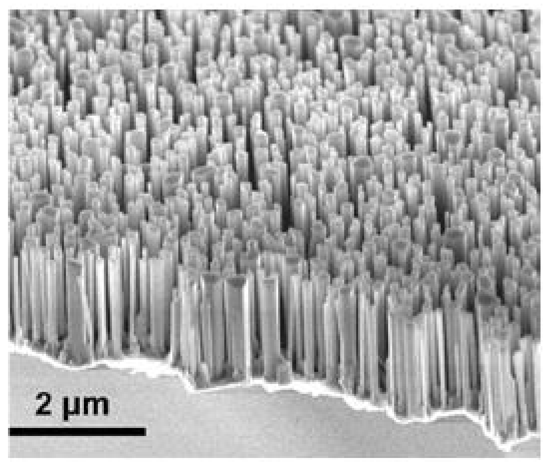

Figure 4. Cu doped ZnO nanostructures (Reference [9])

IV. ZnO Nanostructures Devices

A significant part of the recent research in the field of ZnO-based devices and applications deals with nanostructures and their integration with the mainstream semiconductor materials such as Si, GaN, and organic semiconductors. Furthermore, ZnO has various one-dimensional (1D) nanostructures including nanowires, nanobelts, and nanorods. Because of the small size and high crystal quality, 1D ZnO nanostructures are used as building units to construct different nano devices, such as nano lasers, nano detectors, and nano sensors [13]. Figure 5 shows ZnO nano detectors. On the other hand, ZnO semiconductor nanowires and nanorods have attracted increasing attention due to their physical properties arising from quantum confinement such as electronic quantum transport and enhanced radiative recombination of carriers.

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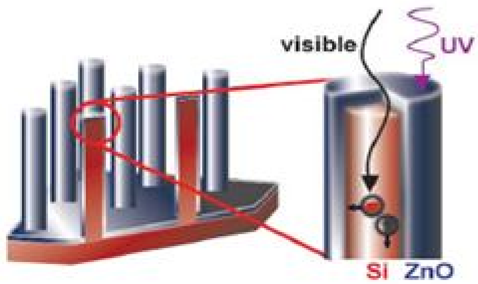


Figure 5. ZnO nano detectors (Reference [14])

V. ZnO Nanowires Devices

The ZnO nanowires devices have created a lot of scientific interest because of their wide potential applications in UV nanolasers, light emitting diodes, solar cells, surface acoustic wave filters, nanogenerators, gas sensors, and photodetectors. The decrease of the size of ZnO nanowire is feasible to obtain more surface area and larger surface to volume ratio. The surface area and surface defects play an important role in photocatalytic activities for ZnO as catalyst. ZnO nanowires with ultrathin diameter are believed to be significant for assembling the nanoscale electronic and photoelectronic devices [15]. Meanwhile, ZnO nanowires can cause a high density of states at the band-edge, due to the quantum confinement effect, and result in a more intensive light emission. ZnO nanowires are also valuable for use as field-induced electron emitters. A thinner diameter ZnO nanowire was reported several research groups [16] in a range of 20-80 nm.

ZnO nanowires have also attracted extensive attention in photodetection. A high photogain (e.g. 108) has been reported several research groups [17]. Several studies have reported improved photosensitivity [18]. The ZnO nanowires has slow recovery of photocurrent has been reported [22]. This slow recovery is due to the surface barrier coincident with the depletion layer which results in the spatial separation of photogenerated electron-hole pairs and slows the photocarrier relaxation rate in the recovery phase by preventing carrier recombination [19,20]. The surface effect on the photocarrier relaxation behavior in ZnO nanowires was investigated by Hong et al. [19,20].

VI. ZnO Nanorods Devices

ZnO nanorods devices based including heterojunction diodes and light emitting diodes have recently been actively investigated by many research groups [21]. The electroluminescence in the UV visible range from ZnO nanorods grown on different substrates has been reported. The heterojunction diodes fabricated from *n*-ZnO nanorods grown on *p*-Si substrates showed 387 nm UV emissions, related to the ZnO near-bandgap recombination, and 535 nm greenish emission related to interface defects. These defects are the defect-free heterojunction interface is highly desirable for the high and stable injection of carriers and excitonic emission of the LED. The possibility of hole injection from the highly doped *p*-type silicon wafer into a single ZnO nanowire has been demonstrated in a planar geometry [22-23]. Figure 6 shows ZnO nanorods in a range of 20-30 nm.

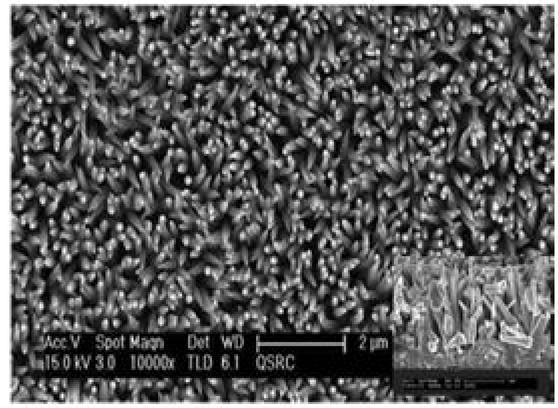
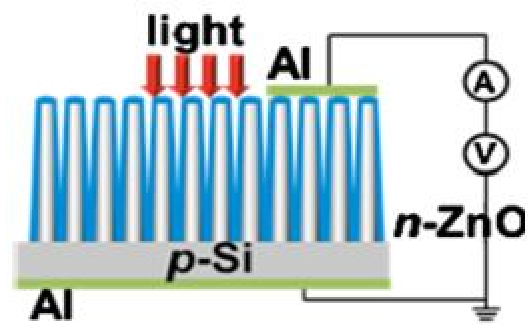


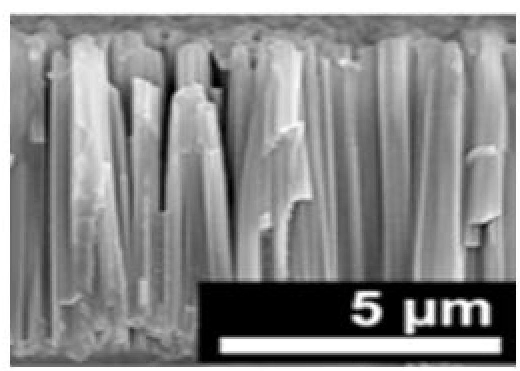
Figure 6. SEM image of ZnO nanorods LED (Reference [23])

VII. ZnO nanostructures Photodiodes

ZnO nanostructures heterojunction photodiodes consisting of *p*-Si and *n*-ZnO nanowire core/shell structures was reported by Um et al. [24]. The conformal coating of an *n*-type ZnO layer that surrounded a *p*-type Si nanowire was used. These photodiodes exhibits enhanced UV and visible responsivities compared to a planar thin film photodiodes. Figure 7 shows ZnO radial heterojunction nanowire photodiodes.



a. Schematic of ZnO Radial heterojunction nanowire photodiodes



b. SEM image of the *n*-ZnO/ *p*-Si nanowire

Figure 7. ZnO Radial Heterojunction Nanowire Photodiode (Reference [24]).

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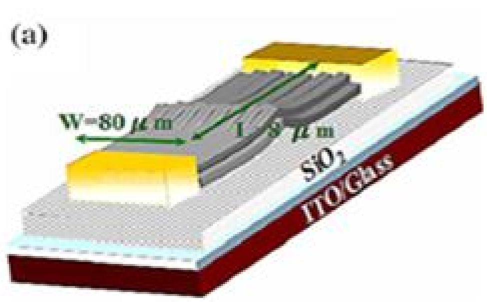
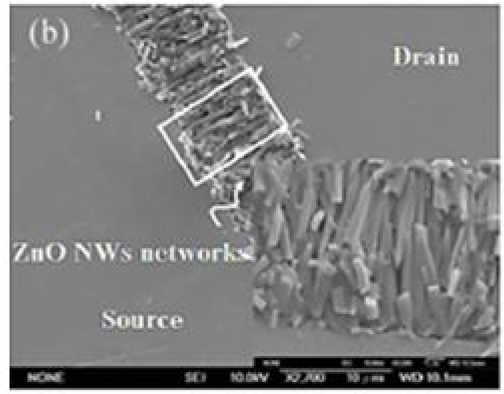
VIII. ZnO nanostructures Field Effect Transistors

ZnO nanostructures nanowire-based field-effect transistors (FETs) are the fundamental element for nano electronics applications. Also, The ZnO nanowires FETs are the basic building blocks for many nanoscale electronic devices. Early studies of ZnO nanowire FETs have focused only on their device performance [25], and photodetection [26]. Recently, there are many studies on the role of geometric properties surface states, and passivation on the transport properties of ZnO nanowire FETs, specifically on the influence of nanowire size and surface roughness associated with the presence of surface trap states at the interfaces. The interface roughness plays an important role in the electronic transport for transistors. Meanwhile, the properties of nanostructures used of nanoscale devices strongly depend on their size and shape. The influence of nanowire size and surface roughness associated with the presence of surface trap densities at ZnO nanowire interface was reported. The interface roughness of ZnO FET does an important role in the electronic transport, also the electronic properties of ZnO nanowire FETs strongly depend on their size and shape. Figure 8 shows the influence of nanowire size and surface roughness associated with the presence of surface trap densities at ZnO nanowire. A review on the tunable electrical properties of ZnO nanowire FETs was reported. The FETs made from surface-tailored ZnO nanowire exhibit two different types of operation modes, which are distinguished as depletion and enhancement modes in terms of the polarity of the threshold voltage. The ZnO nanowires FET shows excellent properties, such as good transparency to visible light, excellent uniformity, and high mobility compared with traditional amorphous/ polycrystalline silicon devices. The stability of the threshold voltage of ZnO nanowires FETs with different temperatures is one of the most critical problems remaining to be resolved for ZnO FETs. The temperature dependency of the device stability of pristine ZnO nanowire FETs temperature range from 323 to 363 K without any treatment was reported by Wang et al. [26]. ZnO nanowire FETs were also reported [27-28]. These ZnO nanowire FETs have a high mobility and using a self-assembled organic superlattice (SAS) as a gate insulator.



a. Schematic of ZnO nanowire FETs



b. SEM image of ZnO nanowire FETs

Figure 8. ZnO nanowire field-effect transistors. (Reference [29]).

IX. Fabrication of ZnO nanostructures

Several fabrication techniques are being used for growing ZnO nanostructures material for devices. These fabrication techniques are based on either solution or gaseous based ambient conditions. The gaseous growth techniques of ZnO nanostructures include the vapour transport process, the catalyst-assisted vapour-liquid-solid process, the metal-organic vapour phase epitaxial growth, spray pyrolysis, hydrothermal methods, thermal evaporation, metal organic vapor phase epitaxy (MOVPE), laser ablation, hydrothermal synthesis, and template-based synthesis.

The fabrication of ZnO nanostructures can be divided into two groups: spontaneous growth and template based growth. Fabrication without a template can occur either by using metal catalysts. The use of metal catalysts has an advantage of achieving aligned and selective area growth. Aligned ZnO nanorods can also be obtained by a hydrothermal method without any metal catalyst [30]. An improvement in alignment of ZnO nanorods perpendicular to the substrate was obtained when zinc acetate was used to prepare the nanocrystalline seed layer instead of ZnO nanoparticles [30].

The growth of ZnO nanostructures such as nanowires and nanorods, vapor-liquid-solid (VLS) method usually applies, where the vapor is exposed to a catalyst such as Au particles. The large-scale arrays with vertically aligned Nanowires can be produced by this method [31]. The partial oxygen pressure and chamber pressure are one of the important parameters influencing the growth mechanism that governs the final structure of the ZnO [32]. By increasing the oxygen content under otherwise identical conditions, nanowires, dendritic side-ranched/comb-like structures, and nanosheets can be synthesized. The catalyst seed layer has an immense influence on nanowires. Control over nanowire growth can be gained by simply varying the Au layer thickness [33].

Epitaxial growth of highly aligned and nearly defect-free nanorods has been observed using CVD on an initial ZnO film produced by pulsed laser deposition (PLD). Low-temperature growth routes for ZnO nanorods have also been reported [34]. The initial ZnO buffer layer affects the morphology and quality of the ZnO nanorods.

Conclusion

In summary, a brief review of ZnO as a nanostructured

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material and devices has been reviewed and discussed. The various shapes of ZnO nanostructured material have been discussed. The difficulty of doping ZnO nanostructured material was explained. Furthermore, ZnO based nanostructured devices were discussed and explained.

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